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Urban Wind Energy - State of the Art 2009

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Abstract (max. 2000 char.):

Wind energy in urban areas is a new area and a rather blank page concerning design criteria, aesthetics, concepts, minimizing costs etc. Even though the potential energy in the flow is much higher on the country side or off-shore, the erection of wind turbines in urban areas is carried out and also shows perspectives regarding e. g. direct use of the energy instead of redirecting the energy to the grid and reduction of transmission loss. Within the area of urban wind energy, different applications are to be distinguished. The main groups are turbines integrated in buildings, small turbines on already existing buildings and free standing turbines in public areas. In this report, a look is taken on the mentioned applications, a short introduction to urban climate is given, followed by a list of already existing small turbines which are compared. Examples in between, field tests and experiments support the understanding. An overview of current projects set the application of wind turbines in the urban environment in a relevant perspective.

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1 INTRODUCTION

Wind energy in urban areas is a new area and a rather blank page concerning design criteria, aesthetics, concepts, minimizing costs etc. Even though the potential energy in the flow is much higher on the country side or off-shore, the erection of wind turbines in urban areas is carried out and also shows perspectives regarding e. g. direct use of the energy instead of redirecting the energy to the grid and reduction of transmission loss. Within the area of urban wind energy, different applications are to be distinguished. The main groups are turbines integrated in buildings, small turbines on already existing buildings and free standing turbines in publicity. Questions like, why should turbines be implemented in cities, what is their usage, where to position which configuration, how about the impact of the every day life of the citizens, has to be answered.

In the first chapter, the different possibilities to introduce wind turbines in the urban area are discussed and accompanied by examples. First a look is taken on concepts with turbines integrated in building's structure. Most of them are ideas and did not make their way from drawing board to construction site. The building type most appropriate for this approach is the high rise building. In the same chapter, examples are listed of the implementation of serial produced small wind turbines on already existing buildings. A short introduction to urban climate follows to understand the difference of off-shore and urban wind conditions. In cities the average wind velocity is significantly lower than the average wind velocity on free land or open water. With that wind turbine designs must be found to respond the unconventional working conditions. Chapter two is handling small wind turbine designs, starting with a description of the pros and cons of vertical (VAWT) and horizontal axis wind turbine (HAWT) concepts, followed by a short list of small wind turbines on the market. Based on the knowledge obtained through the chapters, some alternative ideas and actual installations carried out in Copenhagen are presented in the last chapter.

2 URBAN WIND TURBINES

Until know wind energy production is located decentralized far from cities. Energy production itself and energy saving systems, however, can be found in connection to housing, as e. g. solar energy, geothermal energy and natural ventilation. Wind constitutes one more on-site energy source to be exploited. The question is where to expect sufficient wind potential and how to harvest the energy. Various architects and engineers tried to design an answer. We start here to look at the building integrated wind turbine concepts followed by wind turbines mounted on already existing buildings.

2.1 Turbines Integrated in Buildings

A number of examples of wind turbines in design of urban structures exist. It is a challenging mission to put it into reality though. Most of the designs never made their way from the drawing board to construction site. But the vision is the first step to mission. Integrated wind turbines are most reasonable for high rises, since their height reaches into high wind velocity layers. We will see facts about high rises, some design examples, a green buildings certificate in America will be introduced, which might has motivated the designs and in the end a pros and cons list for turbines integrated in buildings.

Facts about High Rises

- The trend for new buildings goes from using less energy to even produce parts of it by sustainable design [i] [ii] [iii] [iv]
- The main energy consumption states heating and cooling (1/3 is used for heating, Germany)
- Warm air gathers behind glass facades and makes expensive cooling necessary
- New housings are demanding more comfort (no noise, no artificial light, no "thick" air) by cooling, sun protection, natural light
- Buildings are using recyclable construction materials and use rain water
- Public transportation connection is environmentally friendly, because employees or residents are not forced to use cars
- Cooling air can be pre-cooled by soil or sea water

Examples

Conceptual designs of buildings considering wind turbines in the structure are listed below. Autumn 2009 the Bahrain World Trade Centre and the CH2 in Melbourne, were completed. The Perl River Tower and Strata are under construction.

Energy Tower/ Burj Al-Taqa

On the top of the building a patented advanced Darrieus turbine is extracting wind energy. Its flame like shape represents a sign for sustainability and gentle handling with the natural resources. By diverse other energy saving, producing and storing strategies this building is said to be 100% energy self sufficient (ZED = zero emission design).

Location:	Riyadh, Dubai, undisturbed surrounding
Height:	322m
Turbine:	Advanced Darrieus Type, 60m high
Contact:	www.gerberarchitekten.de

Figure 1: Energy Tower [v]

Bahrain World Trade Centre (BWTC)

Three massive wind turbines, measuring 29 meter in diameter, are supported by bridges spanning between BWTC's two towers. Through its positioning and the aerodynamic design of the towers, the prevailing on- shore Gulf breeze is funnelled into the path of the turbines, helping to create greater power generation efficiency. Once operational, the wind turbines will deliver approximately 11-15% of the BWTC tower's energy needs, eliminating around 55.000kg of carbon emissions every year. The wind turbines as an alternative energy source for the buildings will generate 1100 to 1300MWh/year.

Location:	Manama, Bahrain, sea side facing (prevailing wind direction)
Height:	240m
Turbine:	three HAWTs, 29m in diameter
Contact:	www.bahrainwtc.com

Figure 2: Barhain World Trade Centre[vi]

CO_2- neutral City District

The first project as a result of the Masdar Initiative is a new 6 million square meter sustainable development that uses the traditional planning principals of a walled city, together with existing technology, to achieve a carbon neutral and zero waste community. Master planned by Foster + Partners, the initiative has been driven by the Abu Dhabi Future Energy Company, and will be a centre for the development of new ideas for energy production.

Location:	Abu Dhabi, dense walled city
Height:	-
Turbine:	Wind turbine farm, located outside the city district
Contact:	www.fosterandpartners.com

Figure 3: Neutral city district within the Masdar Initiative [vii]

Transbay Transit Centre

Above the 80th floor “Harmonic Turbines”, a sculpture created by the environmental artist Ned Kahn, are positioned. This circular array of visually expressive wind turbines generates power to light the tower’s top. The faster the turbines spin, the more electricity they create, and the more intensely the light glows.

Location: San Francisco close to Golden Gate Bridge, sea breeze
Height: 366m
Turbine: four “harmonic” turbines
Contact: www.pcparch.com

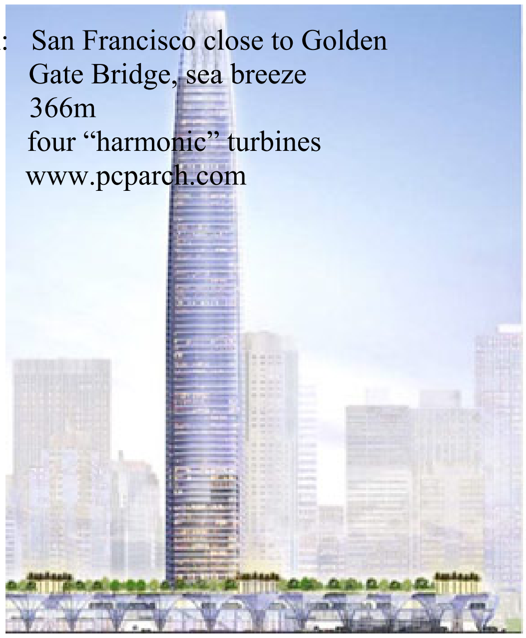



Figure 4: Transbay Transit Centre [viii]

Pearl River Tower

The building minimizes the interference of wind forces and uses them to relieve the structural burdens imposed by high-wind pressures. Pearl River’s sculpted body directs wind to a pair of openings at its mechanical floors. Travelling winds push turbines which generate energy for the building’s heating, ventilation and air conditioning systems. Two vertical axes integrated wind turbines harness prevailing winds from the south and the north with minor efficiency loss. The tower’s curvilinear form further enhances performance by helping to funnel air through turbine inlets in the façade. Wind studies have predicted that the turbines will speed up the wind’s velocity two-and-a-half times.

Location: Guangzhou, China
Height: 310m
Turbine: two encased VAWT
Contact: www.som.com

Figure 5: Pearl River Tower, conceptual design, left, and construction site, right [ix]

Strata (formerly Castle House)

Figure 6: Castle House construction site, left, and conceptual design, right [x]

Three 9m wind turbines integrated into the top of the building are expected to generate sufficient power to drive the energy efficient lighting to the building, an integral part of the sustainable credentials for the building as a whole. The turbines are encased by the structure, fixed in yaw and therefore aligned to the prevailing wind direction. Aerodynamic shaping of the casing shall enhance the power performance.

Location:	South London, low built quarter
Height:	147m
Turbine:	three HAWTs, 9m in diameter, encased, fixed yaw
Contact:	www.stratalondon.com

COR

An exoskeleton shell simultaneously provides building structure, thermal mass for insulation, shading for natural cooling, enclosure for terraces, armatures for turbines, and loggias for congregating on the floor. The building is supposed to be completed in 2011.

Location:	Miami, California
Height:	132m
Turbine:	HAWTs, fixed in yaw, slightly encased
Contact:	www.oppenoffice.com

Figure 7: COR [xi]

And many more

Aeolian Roof	www.2004ewec.info/files/23_1400_derektaylor_01.pdf
CH2, Melbourne	www.designinc.com.au
Lighthouse, Dubai	www.atkins-me.com
Ramsgate Street, London	www.waughthistleton.co
King Abdullah Economic City Wind Towers, Saudi Arabia and Samsung Togok Tower, Seoul	www.som.com
Mersey Observation Deck	www.emergentarchitecture.com

LEED (Leadership in Energy and Environmental Design)

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System, developed by the U.S. Green Building Council (USGBC), provides a suite of standards for environmentally sustainable construction. The hallmark of LEED is that it is an open and transparent process where the technical criteria proposed by the LEED committees are publicly reviewed for approval by the more than 10.000 membership organizations that currently constitute the USGBC. Different LEED versions have various scoring systems based on a set of required "prerequisites" and a variety of "credits" in the six major categories:

Sustainable sites, Water efficiency, Energy and atmosphere, Materials and resources, Indoor environmental quality, Innovation and design process

In LEED v2.2 for new construction and major renovations for commercial buildings there are 69 possible points and buildings can qualify for four levels of certification:

Certified: 26-32 pts; Silver: 33-38 pts; Gold: 39-51 pts; Platinum: 52-69 pts

LEED certification is obtained after submitting an application documenting compliance with the requirements of the rating system as well as paying registration and certification fees. Certification is granted solely by the Green Building Council responsible for issuing the LEED system used on the project.

Arguments for Integrated Wind Turbines

- Economic energy demand is a sales argument
- Alternative to more and more expensive energy sources (oil, gas, electricity)
- Show environmental consciousness
- Get a certificate to stand out of the mass (e. g. LEED)
- Upwind generated by buildings facades increases wind velocities
- Buildings are reaching into high velocity layers, and with that no “useless” wind turbine tower is needed
- The structure can be used to encase turbines to enhance their performance, hide them visually and at the same time make them safer
- Aerodynamic building structure can direct and concentrate wind towards the turbine
- Long transmission lines for energy transportation, linked to significant losses, can be cancelled out

Arguments against Integrated Wind Turbines

- High rises were status symbols to boast wealth; saving money by saving energy might look grasping
- Natural ventilation and wind turbines for electricity production are depending on the wind and are therefore not reliable/ always available
- New surrounding buildings are changing the local wind conditions and must be part of the project as well
- Noise and vibrations close to buildings clash with the desire of more comfort
- Wind velocities in cities are lower and more turbulent than on rural sites
- “Empty space” = expensive volume where people could live in is used by implementing turbines

2.2 Small Turbines on Already Existing Buildings

Another option to implement wind turbines in built-up areas is to mount them on already existing buildings. First a list of suggested check points gives a step-by-step instruction, addressing issues like wind regime, noise and wind turbines design. This is followed by a short explanation of the wind flow pattern around cube shaped obstacles, representing buildings. How small wind turbine implementations were carried out and operated in reality is mentioned thereafter.

Issues to be Investigated

Wind turbines in urban areas have only sparsely been tested. This is the reason to investigate this issue in detail. E. g. a survey was established in 2005 [xii]. This survey will briefly be summarized in the following table.

Table 1: Issues to be investigated to mount wind turbines on domestic housing

Assessment of the wind regime in urban areas and around isolated buildings Carry out resources assessments for wind energy potential in a range of different urban environments (e. g. major city centre, high density terraced housing and city blocks, suburban semi- detached housing neighbourhoods, shopping centre etc.). Develop an improved understanding of local air flows around and over buildings through a combination of computational fluid dynamics modelling and in-situ measurements. Consider developing a dedicated test facility to evaluate the effect of the wind turbine itself on flow over (or around) the building and to evaluate (and possibly certify) different devices.
Assessment of the structural and noise implication of mounting wind turbines on (or within) a building structure Assess the possible combinations of building mounted turbines attachment methods and wall/ roof types to determine installation guidelines on appropriate load bearing capacities. Reassess small wind turbine safety standards to ensure that full range of likely turbulence and wind shear conditions are adequately covered. Carry out a comprehensive review of background noise levels in urban environments and the potential additional contribution of various BUWT (Building Mounted/Integrated Wind Turbines) technologies.
Optimization of wind turbine design for building application Development work to optimize small wind turbines design for operation in the built environment has to be done. Particular attention should be paid to device optimization for operation in enhanced (ducted) flow, cross flow, and high turbulence conditions. Novel blade design and comparison of vertical and horizontal axis turbines should be considered. Optimize inverters, inverter controllers and generators for small, grid connected renewable energy applications. Develop suitable containment or failsafe methods for failed rotors.
Addressing non- technical barriers to BUWT installations Develop a Geographical Information System (GIS) incorporating data on local topography, buildings topology, morphology, orientation, height, wall construction, and roof type (clearly the development of such a database would have additional benefits outside this particular field, including solar energy potential for buildings. Assess the potential BUWT resource in high rise buildings and other structures. Assess non- technical barriers to BUWTs, including capital cost, insurance issues, end user finance and social issues.

Positioning and Mounting

The loads on the roof are to be considered, if turbines should be mounted on already existing houses. The main problem is the turbulent area on roof tops (see Figure 8).

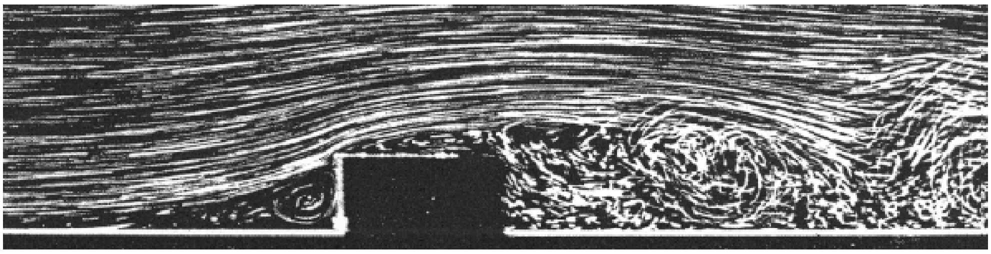


Figure 8: Flow visualized around a squared building [[xii]]

With the turbulence come big changes in loads and inefficient power yield. Therefore high towers are necessary to escape the most turbulent area. Linked to a high tower are high moments induced to the roof structure. That requires a reasonable strong fixing point and a structural analysis of the roof. Prevention or reduction of vibration is achieved by rubber mounts, applied by e. g. Murray O` Laoire Associates for the turbines on Green Building in Dublin (see Figure 9, left) as well as by Prowins`s Provane[[xiii]].

Figure 9: left: Green House in Dublin [[xiv]]; middle: Swift turbine mounting pole [[xv]]; right: ARUP`s VAWTEX [[xvi]]

Proven declares, that vibrations are no problem, if a strong fixing point into a concrete reinforced beam or similar is available, while they use a soft mount system between tower and roof structure to supply additional damping. To come back to the flow field around a building, see Figure 10, besides the high turbulent area on the flat roof top, the walls are subjected to high pressure and low pressure sides respectively, depending on the wind direction. With these pressure differences accelerated and decelerated wind fields are present. Where the suction areas are, an acceleration of the flow will take place.

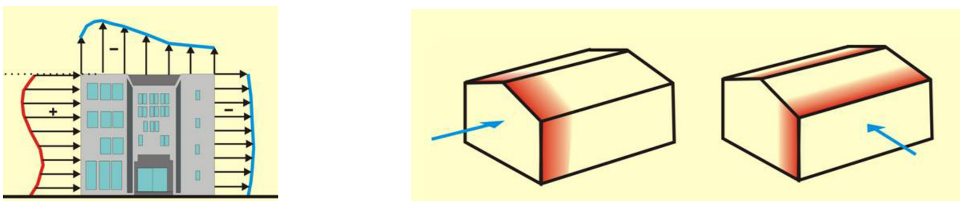


Figure 10: Left: pressure distribution around building; right: wind direction depending suction areas shown by the red colour [[xvii]]

Case Studies

Since a few years, small turbines potentials are taken into account to support the electricity needs. Often the focus is a feasibility study, but does not go further to implementation [xviii]. Some manufacturers made big and incomplete promises to customers. Vibration transmission and with it fatigue breaks of buildings structure and also noise emission due to vibrations brought this market to a fast ending, but at the same time they harmed the reputation of small-scale wind energy. Manufacturers like Ampair are not recommending the installation on roof tops, because the turbines as well as the roof structure are not designed for this application. The group called WINEUR (Wind Energy Integration in the Urban Environment) [xix], carried out feasibility studies, including partners from France, the Netherlands and the UK. In the last few years, the UK has been very active in the field of small or so called micro wind turbines. With manufacturers like Renewable Devices, Proven and Ampair the UK can be called the most experienced partner. Some numbers and implementation principles will be announced here. To get a feeling for the electricity consumption in a household, three different groups, e. g. in Scotland [xx] are stated as following:

- Single person (one adult): 3100kWh/year
- Working couple (two adults): 4100kWh/year
- Family (2 working adults, 2 children at school): 5500kWh/year

Syngellakis carried out a theoretical power production scenario [xxi], based on power curves given by the manufacturers, an electrical conversion efficiency of 97%, on different mean wind speeds and an availability of 70% or 85% respectively. For a mean wind speed of 5m/s and an availability of 70% an annual production of 1452kWh is calculated for the Swift 1.5kW model and for the Airdolphin 1.0kW model a production of 1260kWh. The estimations seem to be optimistic, since the power curve for the Airdolphine [xxii] as well as for the Swift turbine [xxiii] shows a power output of maximum 100W at 5m/s wind. The following case studies were summarized in 2005 by Dutton et al. [xii], partly funded by the Carbon Trust.

The Green Building, Temple Bar, Dublin

Three 3.2m diameter Bergey turbines (rated at 1.5kW at 12m/s) were mounted on the so called Green Building (Figure 9, left). As mentioned earlier, this installation suffered from vibration problem, which was solved by retro fitting rubber mounts and weighting the guys to change the resonant frequencies. Despite this, the installation has not been copied, possibly because the system was constrained by not being allowed to connect to the grid and instead having to charge batteries in parallel with solar photovoltaic panels. The solar panels were oversized for the task and so the turbines now remain largely unused and in fact have been tethered. It is also reported that the blades on these machines cracked- perhaps due to turbulence from the rooftop environment and had to be replaced with new ones manufactured by Proven. This underlines the need to use turbines suited to the built environment.

Factory Building in Belgium

October 2003 three Fortis Montana Wind turbines, 5m in diameter, were installed on the rooftop of a factory building. The energy output is reported by Fortis to be good and they claim that noise is not a problem. However, a problem has been encountered with vibration at high wind speed conditions due to the flexibility of the roof.

Figure 11: Fortis wind turbines fitted to a factory [xii]

North East of England

Fifteen conventional buildings in the Country Durham in the North East of England were re-equipped with different Windseeker wind turbines. Some of the buildings are lime mortared barns for which 500W turbines, mounted 6 to 9m above the building, were chosen. These limits were set because otherwise lateral forces would become too great and the turbine begins to shake mortar from the wall. They were mounted on the western side of the building, here prevailing wind direction. It is possible to buy wind turbine roof mount kits (Southwest Windpower, US; Windsund, UK).

Figure 12: Windseeker 503 [xii]

Lighthouse Building, Glasgow

Developed by University of Strathclyde, from a 1979 patent by G. W. Webster, the ducted wind turbine module is designed to be mounted on a conventional high rise building. The design consists of a 90 degree bent duct, with the inlet in line with the wall face of the building and the outlet on the roof. The turbine rotor is hidden from view, since it is mounted just inside the roof outlet and the drive shaft passes through the duct to a generator housed below. A theoretical power output, considering the local wind conditions and taking photo voltaic panels into account, was calculated as 205kWh/year per unit.

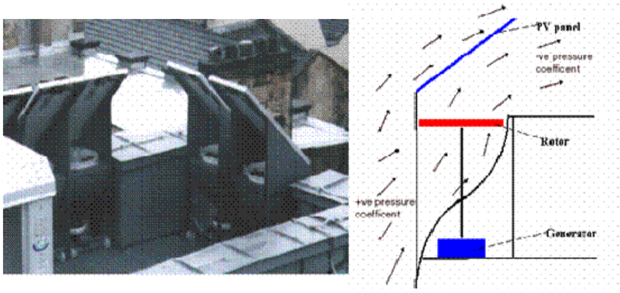


Figure 13: Strathclyde's ducted wind turbine [xx]

Wind Dam

Sponsored by Dartmoor National Park Sustainability Fund and the BT Group plc, the first prototype trial has been completed. There has been a good reaction to aesthetics, noise level and the overall market concept, according to Wind Dam, Truro. The second prototype was planned on a proposed new visitor centre at Haytor (see Figure 14). However, it has now been placed on an industrial building in Cornwall. In parallel with the prototype testing, Wind Dam have now evolved a wind survey database and computer model for sizing and cost/output prediction of low level wind systems. Besides the average wind speed, gusting, other buildings, hedges, hills etc. can all have an effect, either positive or negative, on the wind available to a turbine.

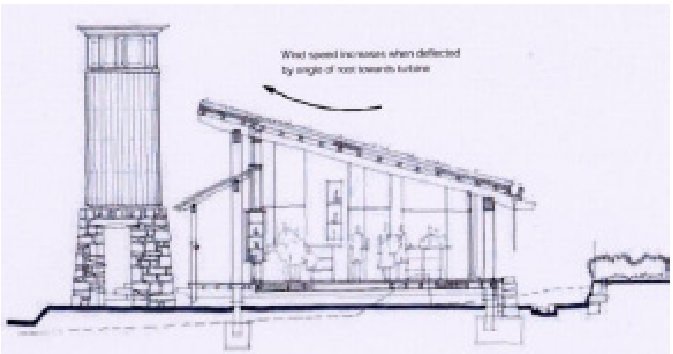


Figure 14: Proposed Haytor Centre [xxiv]

Elephant and Castle

Proven manufactures small wind turbines with rated outputs from 0.6 to 15kW, all of which are available in a Health & Safety (HS) version suitable for installation in public places and on roof tops. The Proven HS turbines are among the few standard production machines on the market today declared suitable for routine installation on roof tops. Proven Energy recommended the installation of a Proven 6 wind turbine on the rooftop of the targeted development, Ashenden House, an eleven storey residential building off the Old Kent Road, London. The Proven 6 was chosen because it is said to be both robust and reliable. The turbine produces up to 12MWh/year, according to Proven [xxv].

Figure 15: Proven 6 on the roof top of the Ashenden House, London [xxiii]

Glasgow School of Art

Proven Energy recommended a Proven 2.5 wind turbine for the targeted iconic Charles Rennie Mackintosh`s designed Glasgow School of Art. The turbine is roof mounted and will produce up to 5MWh/year. The building will not only benefit from lower energy bills but the wind turbine will be used to demonstrate to future and current designers from the School of Art to both think and act green.

Figure 16: Roof top mounted Proven 2.5 turbine [xxvi]

Colombo House

The pilot scheme centres on an installation of two 6kW micro wind turbines and a 15kW solar panel array on the roof of BT Energy & Carbon's Colombo House building on the western side of Blackfriars Road, London. The wind turbines are mounted on 9m masts and are clearly visible from the street and surrounding buildings.

Figure 17 : Two Proven 6.0 turbines on the Colombo House, London [xxvii]

Palestra, London

In 2004, the Swift Rooftop Wind Energy System received official approval for grant accreditation from the Energy Savings Trust in Scotland through the Scottish Community & Householder Renewables initiative. At this time, this grant approval represented the first building mountable wind turbine to receive such grant approval in the UK. At the end of 2006, 14 micro turbines were installed on the roof of Palestra, home of the London Development Agency and the London Climate Change Agency. At the end of January 2007, the turbines were removed. They should have been reinstated, but until now they are still not back and the reason why they were removed is not revealed.

Arguments for Small Wind Turbines Mounted on Buildings

Energy transportation losses are extensive. In some cases the loss accounts about 6%, which could be slashed by on-site energy production. Around 70% of the electricity is used in domestic and office buildings, mostly for heating, light and cooling. A lot of these expenses could be cut down by sustainable design, regarding architectural planning, material science and scientific techniques.

The first step is to reduce energy demands and the second step is to cover most of the remaining needs by renewable energy. Combined with solar panels the costs would be reduced by sharing one transformer, possibly battery, electric cables etc. Additionally, in combination they would cover the whole weather spectra; on hot sunny days the panels will provide energy, is the weather changing to cloudy sky and windy, the wind turbines provide energy. Depending on the global zone different combinations are more recommendable. In the temperate zone, solar energy itself provides energy during the period of the lowest energy demand. Therefore it is sometimes off-phase with the need.

Micro turbines, as they are called for rated power below 10kW, do not need a gear box, which comes along with noise, maintenance and vibration reduction. Low tip speed ratios (~5) have to be attained. In terms of produced energy per square meter of the rotor the modern MW turbines are much more energy efficient. However, the small turbines should be used as a supplement and are affordable for families. Depending on the site the energy which was used to produce a small turbine pays back within a few years. In contrary, the wide spread photo voltaic cells are more cost intense and very expensive in energy to produce them compared to their own energy production. It takes several years until they pay back on the energy level.

Higher surface roughness in towns compared to open fields yields outside the internal boundary layer to a steep increase of velocity with increasing height. So it happens that a slight enhancement in altitude leads to a significant enhancement of power to harvest. An upwind generated by the buildings blockage causes an accelerated air flow above and besides the building and with that wind energy applications becomes attractive. Because buildings themselves are reaching up to several meters a tower structure is not necessary anymore, or at least not high towers. The structure of the buildings can be used advantageous. In summary the arguments for building mounted wind turbines are:

- Less energy transportation loss
- Combined with solar panels, the whole weather spectrum is covered and the two systems can share the same hardware
- No gear box necessary/ less maintenance/ less noise/ less vibrations
- Low wind velocities in cities are enhanced by the upwind by houses or other obstacles
- The background noise in cities is high and covers most of the turbines noise emissions
- Our energy need becomes visible
- Affordable for families

Arguments against Small Wind Turbines Mounted on Buildings

Higher safety is required. A grid/ screen, duct or other measurement can be applied, but e. g. safety grids are connected to losses. On the other hand, in wind tunnels they are used to lower the turbulence intensity, which could be also beneficial in the high turbulent region on roof tops. The drawback is the energy loss connected to this refinement of the flow.

Another opportunity is a duct, which directs and accelerates the wind towards the turbine. It would prevent fatal consequences in case of break down of a wind turbine rotor. Such structures enable the usage of smaller turbines for the same amount of harvested power and especially cut in at lower wind velocities, but demand additional structure and are only recommendable in areas with prevailing wind direction, because the device will not or only very inefficient yaw to align with the actual wind direction.

New materials can be taken into consideration. With new flexibility, more elasticity the crack of a blade could be prevented. QuietRevolution solved the problem with an elastic string running through the whole structure to ensure pieces to stick to the structure in case of a crack. Renewable Devices arranged a circular rim, connecting the blade tips to merge the rotor to one piece. At the same time this device seems to reduce noise emission by restricting the radial flow of air at the tip of each blade. Arguments against building mounted wind turbines are:

- Every roof has its own material, construction and therefore characteristics and with that an universal solution is impractical
- Transmission of vibrations and noise is changing from case to case
- Higher safety demands
- Lower noise emission limit, than on a free field
- High turbulences and fast changing mean wind velocity and direction
- Neighbours might be annoyed by shadow cast and noise while they themselves do not have any advantage of the turbine
- Encasing the turbine with a grid leads to losses

3 URBAN CLIMATE

There is a difference between the wind characteristics outside cities, where big fields of more or less uniform roughness conditions exist, and inside cities, where obstacles and roughness change within short distances (see Figure 18). The wind in cities is less stable and predictable, but turbulent.

Tools like WAsP (Wind Atlas Analysis and Application Program) [xxviii] can not be applied in the city environment. WAsP is a tool to determine wind potential based on information about wind measurements close to the area of interest, roughness parameters of the surroundings and sparsely distributed obstacles in some distance to the point of interest. Usually such tools as WAsP are used to estimate the wind potential of an open and not complex landscape.

To know more about the micro climate on chosen sites in a city environment, possibilities are computational fluid dynamics calculations, on-site measurements, or wind tunnel tests, including the neighbouring area to a sufficient extent. The local wind climate is dependent on its surroundings, so e. g. its distance to the suburbs, to a park, lake or to a high trafficked street. In general the wind velocities in cities are lower and more turbulent.

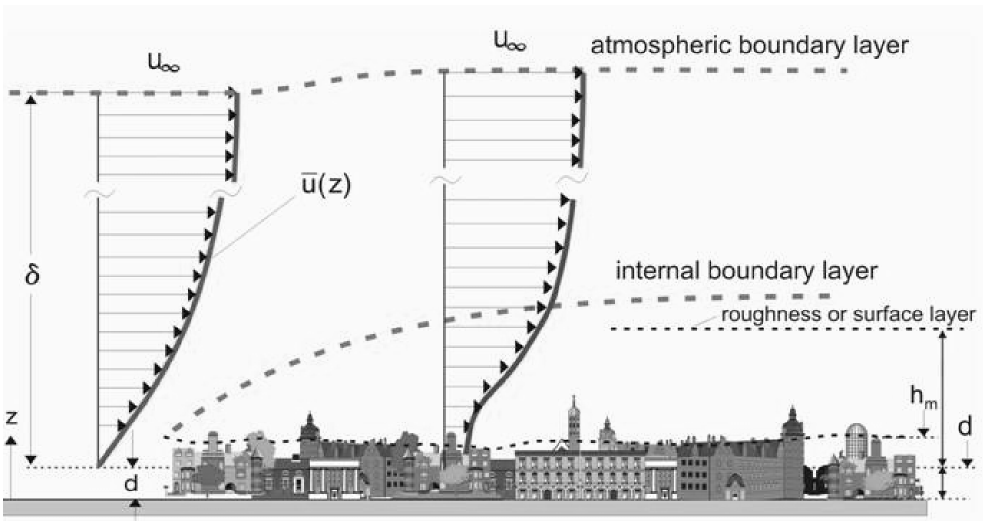


Figure 18: Step change in surface roughness incorporates a changing boundary layer profile [xvii]

3.1 Test Facilities

To simulate the micro wind at the spotted location in a wind tunnel, one possibility is to scale down the city, respect certain roughness and equality rules and chose a method to visualize and/or preferably measure the flow situation. First of all, the boundary layer profile upstream the model shall be shaped. That can happen with the help of vortex generators and roughness elements (see Figure 19). Behind the shaping section follows a measure section to validate the right arrangement of the roughness elements etc. If the model set up and the full-scale conditions shall correspond, equality criteria for the model itself have to be satisfied but also for the incoming flow. Gromke [xxix] investigated the development of the so called Prandtl layer, reaching up to 50-100m in nature and is therefore relevant for urban buildings, city canyons and urban wind energy.

The entire boundary layers can be described by the logarithmic profile or by the power law,

$$\frac{\bar{u}_z}{\bar{u}_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha},$$

with $\bar{u}_z$ as the mean wind velocity at the corresponding height z, $\bar{u}_{ref}$ is a known velocity at the height z_{ref} and α is describing the shape of the profile. For wind profiles in city centres α=0.38 turned out to be appropriated [xxix]. The most important equality number to be kept is the Reynolds number.

It is defined as $$\mathrm{Re}_o = \frac{u_o l_o}{\nu_o} = \mathrm{Re}_m = \frac{u_m l_m}{\nu_m},$$

where the indices *o* stands for original and *m* for model. The parameter *l* gives a geometrical characteristically length e. g. the height of a certain building, *u* is the wind velocity and *v* is the viscosity of the flowing fluid. In environmental aerodynamics, the model objects are mostly sharp edged and barely aerodynamically shaped as for airplane wings. In this case a limited Reynolds number can be applied. That means, if a Reynolds number of around 10 000 is exceeded, the inert force are very big and the friction forces are predominant. With that the wake area behind, e. g., a house is not changing significantly with Reynolds numbers increasing beyond *Re*=10 000.

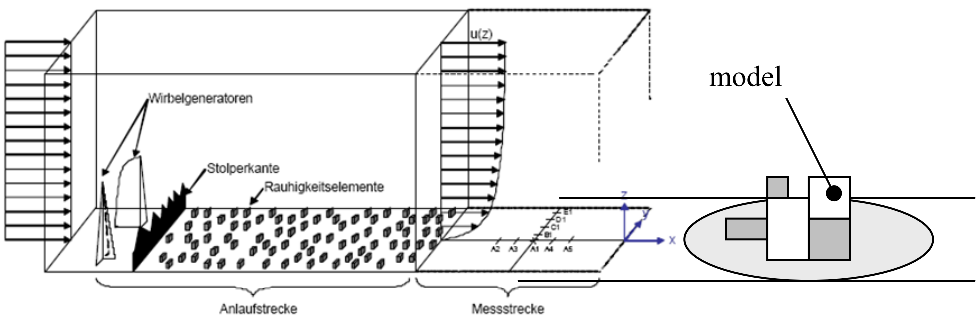


Figure 19: Set up to generate an atmospheric boundary layer in a wind tunnel [xxix]

Considering the height of a tower, l_o=100m, the air viscosity, ν_o=1.5 * 10^{-5} m^2/s, and varying wind velocities with $u_{o,1}$=4m/s (low winds), $u_{o,2}$=5m/s (average wind at ca. 15m without obstacles), $u_{o,3}$=10.3m/s (average wind at 100m), the Reynolds numbers would be Re_1=26.6*10^6, Re_2=33.3*10^6 and Re_3 =68.7*10^6. With these numbers the limit for the restricted Reynolds number is far exceeded. For a wind tunnel model a Reynolds number of at least 10 000 should then be applied. Scaling down the buildings with a factor of 1:300 would result in a tower height of 0.33m and states a size which is feasible in order to fit in a wind tunnel test section. The geometrical scaling factor 1:300 is also satisfying the Reynolds Roughness Criterion for urban districts [xxix]. With the height for the model tower, l_m=0.33m, the same air viscosity and the minimal restricted Reynolds number of *Re*=10 000, a minimum velocity of u_m=0.4545m/s has to be applied in a wind tunnel. Depending on the measurement device and the purpose of the measurement device a scale of 1:300 might result in too small models. Measurements probably can not be carried out in an accurate way.

3.2 Urban Canyon

Cities are a kind of a landscape. Some areas are lower built, some areas are dominated by very high buildings, in one area there are a lot of parks in the other area there are a lot of parking lots and yet in other areas there is a mix. One very characteristic arrangement is houses aligned along streets. It creates an urban canyon. A lot of investigations were done in this field, mostly concerning pollution or poison gas particle distribution. In case of a perpendicular approach of the wind towards the street, a vortex is developing in the street canyon (see Figure 20, top). Figure 20, middle, depicts the three dimensional vortex situation respecting the bordering buildings or the ends of a long building. If the wind is approaching the street canyon parallel, the wind gets funnelled by the buildings, with that accelerated and behaving like a fluid in a tube (see Figure 20, bottom).

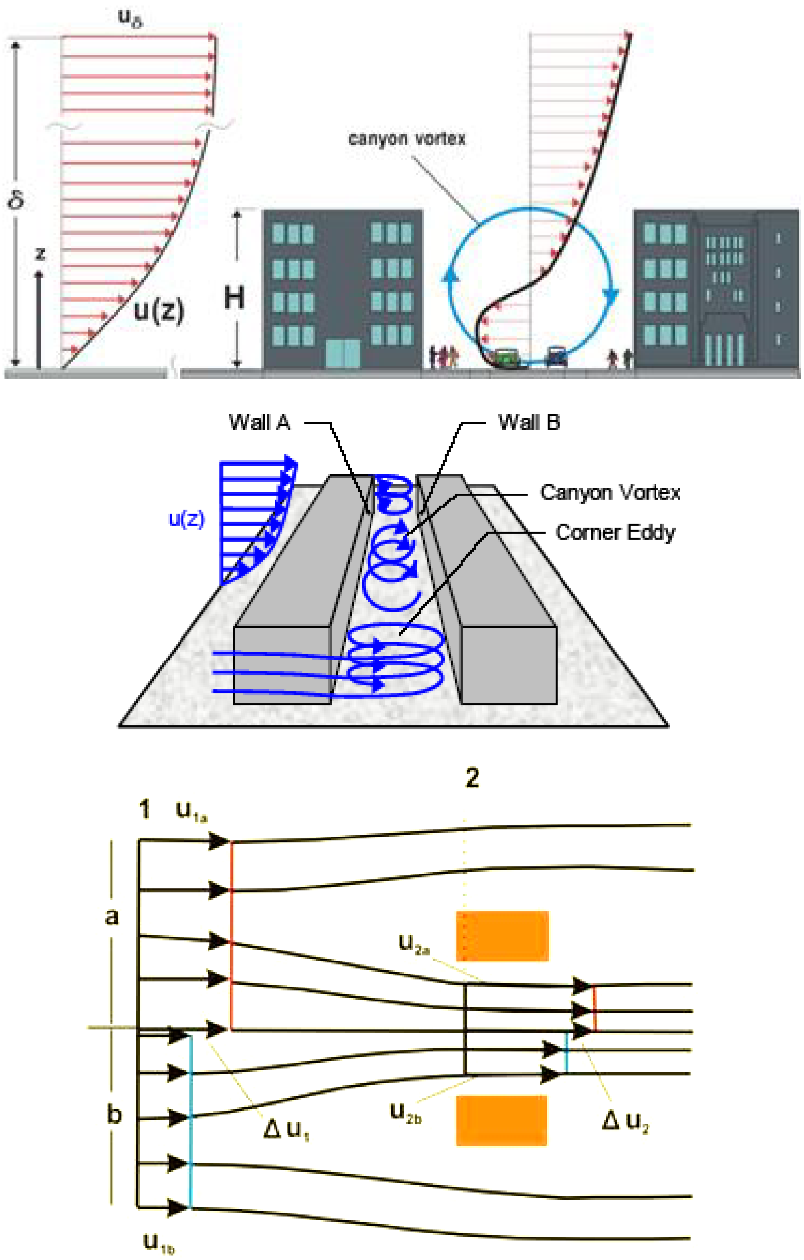


Figure 20: Top: circulation for rectangular approaching winds [xvii]; middle: 3D circulation [xxx]; bottom: funnelling of parallel approaching winds [xvii]

3.3 Smoke Bomb Experiment

Besides wind tunnel tests the possibility exists to measure wind on-site, while a campaign should include at least useful data of one year. If the wind behaviour in a vast area is needed, wind measurements at few points are not sufficient. Wind measurements are commonly carried out on a few spots, but we need as well information of the wind in between the spots. This can be done by computational fluid dynamical calculations.

Qualitative information can be obtained by visualization in reality, full-scale or again in the wind tunnel. One opportunity is to use smoke bombs (see Figure 21). The disadvantage of visualization on-site is that the conditions are seldom stable. Furthermore, the visualization is showing the conditions for only this very moment. To get an idea of the course of the flow, smoke is a convenient way to trace. Information about wind velocities, turbulences etc. are not extractable from a smoke bomb experiment though.

Figure 21: Smoke bomb v_{wind}=5m/s: boundary layer profile, proceeding over grass, compressed by a bump; Thyborøn 2008

3.4 Characteristics of Urban Sites

In the following five different types of sites are described.

Location One: Siting at Remote Areas

Wind condition:	Undisturbed wind flow, influenced by only one or a few obstacles
Location:	Remote place, no neighbouring buildings
Turbine:	HAWT, maybe four bladed (compared to three bladed rotor, noise emission is reduced by 5dB)

Remote places like camping bases in mountains or farms outside populated areas can use free standing turbines with a sufficient high tower. In case of an advantageous location in matter of upwind on a hillside, this should be taken into account. The wind conditions are undisturbed, besides the influence of the building itself, therefore the turbine can be positioned in context with the aerodynamic influence of the building or in an appropriate distance from the building to avoid the interaction. The positioning has to pay respect to noise emission, vibration transmission and shadow casting.

Location Two: Siting at Built-Up Areas of the Same Height

Wind condition:	Frequently changing wind direction, turbulent
Location:	Area of low built houses, suburb and city centre
Turbine:	VAWT, size is depending on location and usage

An area with buildings of the same height is exposed to urban canyon effects. Depending on vegetation, open places, orientation of the buildings to each other, the decision is very site depending. Large scale phenomena like urban canyon effects might be detected and used in certain ways, but small, very fast changing wind direction are not controllable and make a vertical turbine most attractive. If turbines are going to be implemented on roof tops, then it is necessary to circumvent the recirculation area induced by the leading edge of a building. Fixation of the turbine to the buildings structure is a big issue. If the turbines are going to be mounted on already existing buildings, it is essential to know about the roof construction and maximum loads from the turbine. A vibration survey has to be accomplished.

Location Three: Siting at High Buildings/ Skyscraper

Wind condition: Prevailing wind direction
Location: Dense populated area, planning a skyscraper
Turbine: Venturi encased HAWT, integrated in buildings structure, fixed yaw

If the wind is predominant from one direction, and the area is planning to have a skyscraper, then the ideal turbine would be implemented in the upper part of the skyscraper, encased by a Venturi shaped tubing. The building has to be aligned with the mean wind direction and respecting other adjacent high buildings, while the turbine is not free to yaw. It must be ensured, that future buildings in the neighbourhood are not going to change the wind condition dramatically, because the turbines are not demountable and the tunnels through the building would be useless. In experimental comparisons of a non-ducted with a ducted turbine, the power output of the ducted one was higher [xxxi]. When they were free to yaw, the ducted turbine showed 1.16 times higher power than the non-ducted. Fixed in yaw the ratio was 1.65. However, in terms of cost per kWh it might turn out that the Venturi ducted turbine is too costly. Whether this tubing should be used or not should also be considered together with safety, aesthetics and vibration reasons.

Location Four: Siting at Free Fields in Urban Areas

Wind condition: Free wind, almost undisturbed
Location: Park, parking lot, boardwalk (moderately frequented by people)
Turbine: HAWT or VAWT with direct usage of energy (fountain, light etc.)

In cities exists areas without buildings. In parks, for example, free fields exist, while they are surrounded by city environment and some trees. Therefore the wind is disturbed at the entrance to the free field and changing from one roughness class to another takes a while until the corresponding boundary layer is developed. The same applies for parking lots, while the parking lot situation is changing permanently. What is special about these areas is that they are only frequented by daytime or at least during the night these areas are not used for living. That is why noise emission during the night is not a big issue. On the other hand, parks are meant for recovery and traffic noise is not present.

Location Five: Siting at Water Channels

Wind condition: Funnelled wind, accelerated, urban canyon conditions
Location: Bridges, over a housing bordered channel
Turbine: VAWT integrated in structure, or HAWT

Water states a surface with very low roughness. It implies high velocities at low altitude. Depending on the shaping of a bridge crossing a channel different positions of different wind turbine types are appropriate. If the prevailing wind direction is parallel to the channel, the wind will be accelerated and offer a site for turbine implementation. If the wind approaches the “urban canyon” perpendicular, a vortex region will be governing the bridge surrounding and with it, change the load situation on the rotor and especially on the tower significantly.

4 SMALL TURBINES

Several small turbines are on the market, while some are more successful and some less. One big drawback is definitely the lower efficiency compared to large scale turbines. Large wind turbines, depending on the chosen site, are paying back on the energy level within only a few months (~three month). In contrast, small turbines need several years until they have produced the amount of energy, which was necessary to produce and operate them. Paul Gipe is administrating a homepage, discussing small turbines with a critical eye [[xxxii]]. He states that large wind turbines produce ~ 9/5 more energy than small turbines per swept area. At a site with a 5m/s average wind speed at hub height, it would require a small wind turbine with nearly 40m² of the wind stream to meet the needs of the typical North American home without electric heat. This could be supported by a wind turbine the size of e. g. the Bergey Excel with a 7 m diameter rotor.

[remark]:>>The typical European household uses almost one-fourth of the typical North American consumption. A German family, for example, will need only 4m² of the wind stream to meet their needs from a large wind turbine or about 8m² from a small wind turbine. This is equivalent to a small wind turbine with a rotor diameter of 3.2m (10ft). North Americans living off-the-grid may reduce their consumption to the levels typical of Europeans. Some may use even less electricity. Thus, they may be able to meet all their electricity needs with a hybrid wind and solar system. However, they are the exceptions. If you're a North American, be very wary of any wind turbine promoter who says that their small wind turbine with a rotor only 1-2 meters in diameter will meet all your electricity needs. They either don't know what they are talking about, or they are preying on an unsophisticated market and you don't want to do business with them. <<

(Gipe [[xxxii]]; Small Wind Turbine Size to Meet Household Consumption)

The dominant concept with a Horizontal Axis Wind Turbine (HAWT) using three blades upstream of the tower has shown to be reliable and cost effective. However, this concept is developed for use on MW size turbines to sites with relatively low turbulence intensity. Considering wind turbines in the urban context and determining appropriate concepts needs an open-minded approach, where the weight on different design drivers has been changed to put new emphasize on noise, aesthetics, fast varying flow directions and a high fraction of manpower cost per kWh. Therefore, new concepts compared to the current dominating concept should be considered such as Vertical Axis Wind Turbines (VAWT) and other types of HAWTs.

4.1 Vertical Axis vs. Horizontal Axis Wind Turbines

Vertical axis wind turbines specifically designed for an urban environment offer a complementary strategy for power generation to conventional wind farms. Sizes in rotor diameter can range from 1-20m and power output from 100W-100kW. To gain public acceptance, much thought has to be put into an aesthetic and reliable design. The principal advantage of modern vertical axis wind machines over their conventional counterparts is that VAWTs are omnidirectional- they accept the wind from any direction. This simplifies their design and eliminates the problem imposed by gyroscopic forces on the rotor of conventional machines as the turbines yaw into the wind. The vertical axis of rotation also permits mounting the generator and gear at around ground level. Vertical axis turbines, like their conventional brethren, can be divided into two major groups: those that use aerodynamic drag to extract power from wind, e. g. the Savonius type, and those that use lift from an airfoil. Further, VAWTs using airfoils subdivide into those with straight blades, e. g. the H-rotor type, and those with curved blades, e. g. Darrieus type (see Figure 22). The simplest configuration uses two or more straight blades attached to the ends of a horizontal cross arm. Unfortunately, this configuration permits centrifugal forces to induce severe bending stresses in the blades as their point of attachment. During the 1920s French inventor D. G. M. Darrieus patented a wind machine that cleverly dealt with this limitation. Instead of using straight blades he attached curved blades to the rotor. When the turbine was operating the curved blades would take the form of a spinning rope held at both ends. This troposkein shape directs centrifugal forces through the blade's length towards the points of attachment, thus creating tension in the blades rather than bending. Because materials are stronger in tension than in bending, the blades could be lighter for the same overall strength and operate at higher speeds than straight blades. Darrieus turbines were never reliably self starting. Their fixed-pitch blades can not drive the rotor up to operation speed from standstill unless the blades are parked in just the right position relative to the wind. By using straight blades H-rotors can vary blade pitch as the blades orbit around the rotor's axis. The H-rotor has one important advantage over the Darrieus design. It captures more wind. The intercept area of an H-rotor is a rectangle. For the same size wind machine- that is, where the height and diameter are the same- the H-rotor will sweep more area than an ellipse does [xxxiii].

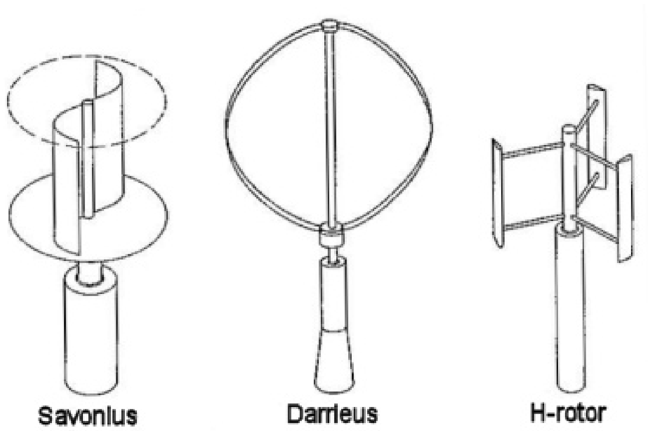


Figure 22: VAWT concepts (from left to right):Savonius, Darrieus and H-rotor type[xxxiv]

As mentioned above the VAWTs are omnidirectional. The HAWTs, however, have to align with the wind direction in order to be most efficient. This horizontal alignment is commonly called yawing.

Various yawing concepts exist to align with the wind direction, passive and active. The conventional HAWT concept in MW size is equipped with an active yawing system, which can e. g. consist of a wind measurement device detecting the current wind direction, and a motor to adjust the rotor to the new wind direction. Small-scale wind turbines are usually designed with a passive yaw system. One of the oldest passive yaw systems is the wind vane, which can be seen in Figure 23 in the middle. The vane has to have an appropriate area and arm, so that in case of changing wind direction a pressure force is imposed on the vane face and generates a moment great enough to align the rotor. Another passive yaw system is included in a less frequent wind turbine concept, the downwind concept.

In general the HAWTs can be divided in the upwind and downwind concepts. A wind turbine design is called upwind concept when the position of the rotor relatively to the tower lies upwind. That means, that the wind first passes the rotor plane and then the wind passes the tower (see Figure 23 to the left and middle). A wind turbine design is called a downwind concept when the position of the rotor relative to the tower lies downwind. That means that the wind passes the tower first and then the rotor (see Figure 23 to the right). With the downwind concept the rotor aligns with the wind direction without any additional construction or sensors.

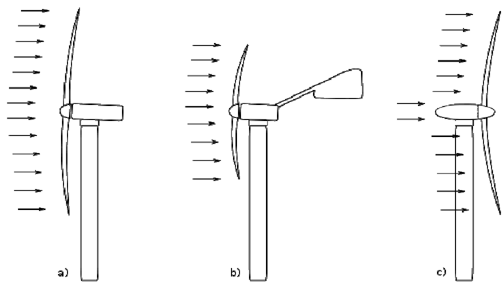


Figure 23: HAWT concepts (from left to right): upwind type with active yaw; upwind type with passive yaw; downwind type with passive yaw [xxxv]

Summarizing the comparison between HAWTs and VAWTs, the advantages of vertical turbines are:

- Independent of wind direction
- Generator can be located on the ground (structural advantage and maintenance accessibility)
- Less noise (Darrieus type has no tip vortex)
- Withstands high turbulences
- Symmetric and aesthetic

While the disadvantages are:

- Low Cp ($\sim Cp_{HAWT}$=0.45; $\sim Cp_{VAWT}$=0.35)
- Not self starting
- Changing angle of attack over one rotation
- Fixation of the upper end of the axis is needed (for big turbines)

4.2 Examples

In the following some examples of small wind turbines are introduced. Since we are looking at small wind turbines, all of the listed HAWTs are equipped with a passive yaw system. HAWT downwind concepts as well as upwind concepts are among the chosen ones. There are far more products on the market. The selection has no special motivation, besides the aim of showing different designs and performances. As far as possible, technical data is summarized, extracted from supplier's information or other sources found on the internet.

Proven

The Proven turbines have a direct drive generator, which operates without a gearbox. The generator load is monitored to keep blades rotating at a low speed. The blade tip speed is kept very low to minimise noise. The power connectors and turbine brake are accessible at the base of the mast. Proven offers three different turbines. For all of them the patented "Furling" (in winds above 12m/s, the Proven's blades twist to limit power in response to high rpm) applies.

Figure 24: Proven 6 installed in Blackpool [xxxvi]

*Table 2: **Proven**; technical information*

Model:	**Proven 2.5**	**Proven 6**	**Proven 15**
Rated power [W]:	2500	6000	15000
Cut In [m/s]:	2.5	2.5	2.5
Cut Out [m/s]:	none	none	none
Survival [m/s]:	70	70	70
Rated [m/s]:	12	12	12
Rotor Type:	HAWT, Downwind, Self Regulating	HAWT, Downwind, Self Regulating	HAWT, Downwind, Self Regulating
No. of Blades:	3	3	3
Blade Material:	Polypropylene	Glassthermoplastic Composite	Glassthermoplastic Composite
Rotor Diameter [m]:	3.5	5.5	9
Generator Type:	Brushless, Direct Drive, Permanent Magnet	Brushless, Direct Drive, Permanent Magnet	Brushless, Direct Drive, Permanent Magnet
Rated rpm:	300	200	150
Head Weight [kg]:	190	600	1100
Mechanical Brakes:	Yes	Yes	Yes
Noise [5m/s]:	40 dBA	45 dBA	48 dBA
Noise [20m/s]:	60 dBA	65 dBA	65 dBA

Ampair

Ampair is a turbine manufacturer, while the application ranges from underwater turbines, over wind generators for small sized yachts and lower power land based application, to wind generators for higher power land based applications where the connection is to an electrical network. All models are able to withstand marine environment.

Figure 25: Ampair 600 installed on a brick wall [xxxvii]

*Table 3: **Ampair**; technical information*

Model:	**Ampair 600**	**Ampair 300**	**Ampair 100**
Rated power [W]:	698 (into grid)	300	100 (max)
Cut In [m/s]:	3.0	3.0	3.0
Cut Out [m/s]:	n/a	n/a	n/a
Survival [m/s]:	n/a	n/a	n/a
Rated [m/s]:	11	12.6	n/a
Rotor Type:	HAWT, Upwind	HAWT, Upwind	HAWT, Upwind
No. of Blades:	3	3	6
Blade Material:	GRP construction	GRP construction	Glass filled polypropylene
Rotor Diameter [m]:	1.7	1.2	0.93
Generator Type:	Direct Drive, NeFeBr, Permanent Magnet	n/a	n/a
Rated rpm:	n/a	n/a	n/a
Head Weight [kg]:	16.0	10.5	12.5
Brakes:	Pitch control & dump load	Pitch control	n/a
Noise [5m/s]:	max 1-3 dBA above background noise	n/a	n/a
Noise [20m/s]:		n/a	n/a

T. Urban

T. Urban is a small wind turbine, especially designed for the urban environment. The project TURBan is coordinated by INETI (Instituto Nacional de Engenharia, Tecnologia e Inovacão), Portugal, and co-sponsored by ADI, the Portuguese Innovation Agency under program DEMTEC. At the EWEC 2008 conference the model was presented. Until this date one turbine was installed. It is located in Lisbon, while the site is not optimum for its operation. It shall be commercially available in 2009, they claim.

Figure 26: A full scale model of T.Urban at EWEC 2008

*Table 4: **T. Urban**; technical information*

Model:	**T. Urban**	Rotor Type:	HAWT, Upwind
Rated power [W]:	2500	No. of Blades:	3
Cut In [m/s]:	3.5	Blade Material:	n/a
Cut Out [m/s]:	25.0	Rotor Diameter [m]:	2.3
Survival [m/s]:	n/a	Generator Type:	Synchronous-type Permanent Magnet (PMG)
Rated [m/s]:	13.5		

QuietRevolution

The QuietRevolution was designed by XCO2 in response to increasing demand for wind turbines that work in the urban environment, where wind speeds are lower and wind directions change frequently. Helical (twisted) blades shall ensure a robust performance in turbulent winds. Noise and vibration shall be low. Since 2007 several installations were accomplished and roof top installation instruction is available.

Figure 27: Installation at Kings College, Wimbledon; November 2007 [xxxviii]

*Table 5: **QuietRevolution**; technical information*

Model:	**QuietRevolution**	Blade Material:	Epoxy Resin
Rated power [W]:	6000	Rotor Diameter [m]:	3.1 (and 5m high)
Cut In [m/s]:	4.5	Generator Type:	Direct Drive Permanent Magnet
Cut Out [m/s]:	16.0		
Survival [m/s]:	n/a	Rated rpm:	n/a
Rated [m/s]:	12.5	Head Weight [kg]:	n/a
Rotor Type:	VAWT	Brakes:	Electro-magnetically actuated
No. of Blades:	3	Noise [4m/s-10m/s]:	below ambient noise level

Turby

Different from the Darrieus design and similar to the QuietRevolution, the designer of the VAWT Turby fixed the blade distance to the shaft. In this way experiences the whole blade the same wind speed and rotational speed. To reduce the inevitable vibrations due to the change of the angle of attack between +20º and -20 º resulting in a change of the mechanical stress in the blades two times per revolution, Turby's developers chose an odd number of blades of a helical shape, making all changes pass off gradually. On the homepage some examples of installations in urban environment can be found.

Figure 28: Turby [xxxix]

*Table 6: **Turby**; technical information*

Model:	**Turby**	Blade Material:	Composite
Rated power [W]:	2500	Rotor Diameter [m]:	2.0 (and 2.65m high)
Cut In [m/s]:	4.0	Generator Type:	Synchronous Permanent Magnet
Cut Out [m/s]:	14.0		
Survival [m/s]:	55.0	Rated rpm:	120-400
Rated [m/s]:	14.0	Head Weight [kg]:	136.0
Rotor Type:	VAWT	Brakes:	Electrical, short circuiting
No. of Blades:	3	Noise [4m/s-10m/s]:	n/a

Energy Ball

This Energy Ball is being characterized by the six curved rotor blades which are attached to the rotor hub with both ends. When the Energy Ball rotor turns it resembles a sphere, and as a distinct feature the wind blows parallel to the rotor hub through the rotor. This wind flow direction (flow pattern) forms a key contrast with classic sphere shaped Darrieus turbines, whereby the wind hits the blades perpendicular to the rotor shaft or rotor hub. Due to the aerodynamics characteristics of the Energy Ball, it shall create a wind flow pattern that converges first and is then accelerated through the rotor, resembling the rapids in a river (the so-called Venturi effect). This shall translate into a higher aerodynamic efficiency compared to conventional wind turbine designs, explains the company.

Figure 29: Energy Ball installed on the top of a public lamp [xl]

*Table 7: **Energy Ball**; technical information*

Model:	**Energy Ball V100**	No. of Blades:	6
Rated power [W]:	100 (max. 500 at 17m/s)	Blade Material:	Reinforce glass fiber polyester
Cut In [m/s]:	2.0	Rotor Diameter [m]:	1.1 (and 1.3m long)
Cut Out [m/s]:	n/a	Generator Type:	Brushless, Neodium Permanent Magnet
Survival [m/s]:	40.0		
Rated [m/s]:	10.0	Head Weight [kg]:	30.0
Rotor Type:	HAWT, kind of Venturi principle	Brakes:	Electrical
		Noise	"almost none"

Super Eco

The Korean company IR Wind Power developed a turbine design, which has to prove its performance. A vertical axis turbine with a wind vane to orientate the shovel, mounted on the front, towards the wind direction shall power street lamps. An up-scaled version is planned to even produce 10MW. Some of the small versions are already operating.

Figure 30: Super Eco model at the EWEC 2008

*Table 8: **Super Eco**; technical information*

Model:	**IRTS-500W**	**IRTS-10M**
Rated power [W]:	500	10000000
Cut In [m/s]:	2.5	4.0
Cut Out [m/s]:	20.0	25.0
Survival [m/s]:	60.0	60.0
Rated [m/s]:	9.0	15.0
Rotor Type:	VAWT drag type with shovel and vane	VAWT drag type with shovel and vane
No. of Blades:	5~7	7~13
Blade Material:	Poly-carbonate/ Glass-fiber	n/a
Rotor Diameter [m]:	3.6 (and 1.3 high)	280 (and 15 high)
Generator Type:	PMSG	PMSG
Noise	"noiselessness"	"noiselessness"

4.3 Comparison of Small Wind Turbines

Energy is extracted by decelerating the wind and transforming kinetic energy into electricity. A theoretical optimum of the power coefficient is given by Betz and states the maximum, 16/27 of the wind power can be used, while the power coefficient is defined as

$$C_P = \frac{P}{\frac{1}{2}\rho v_{wind}^{3} A_{rotor}}.$$

P is the power produced at a certain wind velocity, ρ is the density of the air and here considered to be 1.225kg/m^3, which is the density at normal conditions (15ºC and 1013hPa), A_{rotor} is the sweeping area of the rotor and v is the wind velocity far away from the influence of the wind turbine. In general, C_P gives the efficiency of the turbine operation; the produced power over the power available in the wind. Some turbine manufacturers give in the technical specifications a chart of power over wind velocity. For the selected turbines, see above, mostly the rated power is given and the corresponding rated wind velocity. Based on these values, C_P is calculated and summarized in Table 9.

Since the theoretical optimum is C_P=0.59, considering Gipes factor of 5/9 [[xxxii]], we end up with a maximum of C_P=0.33. The C_p values are based on the rated power and calculated with the corresponding rated wind velocity, given by the manufacturers. Most of the time, the wind velocity will be below the rated velocity and with it below the rated power. Depending on the chosen site, one or another turbine would be recommendable. In general, it can be said, that the smaller the rotor, the bigger the loss compared to the harvesting gets. It is important to investigate the whole power curve to decide which performance fits to the ruling wind situation. The IRTS-10M is probably not built yet and the numbers seem not to be correct.

Table 9: Comparison of the turbines C_p based on the rated power

MODEL	**Proven 2.5**	**Proven 6**	**Proven 15**
swept area [m²]	9.2	23.8	63.6
C_p [-]	0.25	0.24	0.22
MODEL	**Ampair 600**	**Ampair 300**	**Ampair 100**
swept area [m²]	2.3	1.1	0.7
C_p [-]	0.38	0.22	**0.14**
MODEL	**T. Urban**	**QuietRevolution**	**Turby**
swept area [m²]	4.2	15.5	5.3
C_p [-]	**0.4**	0.32	0.28
MODEL	**Energy Ball V100**	**IRTS-500W**	**IRTS-10M**
swept area [m²]	1.0	4.7	4200.0
C_p [-]	0.17	0.24	**1.15**

In Figure 31 the *Cp* values are drawn for different wind velocities. The values are calculated on base of available power curves. All of the power curves were published by the manufacturer, weather in brochures or their homepages on the internet. Most power curves are not referring to results from field test measurements, but are theoretical power curves, as values like e. g. *Cp*=0.53 let assume. Since no numerical tables were available, values were read out of charts and are with that linked to inaccuracies. Since the power values for small wind velocities are very small as well, especially here the read- out accuracy is very low. That might explain the relatively high and questionable *Cp* values for the low wind velocities.

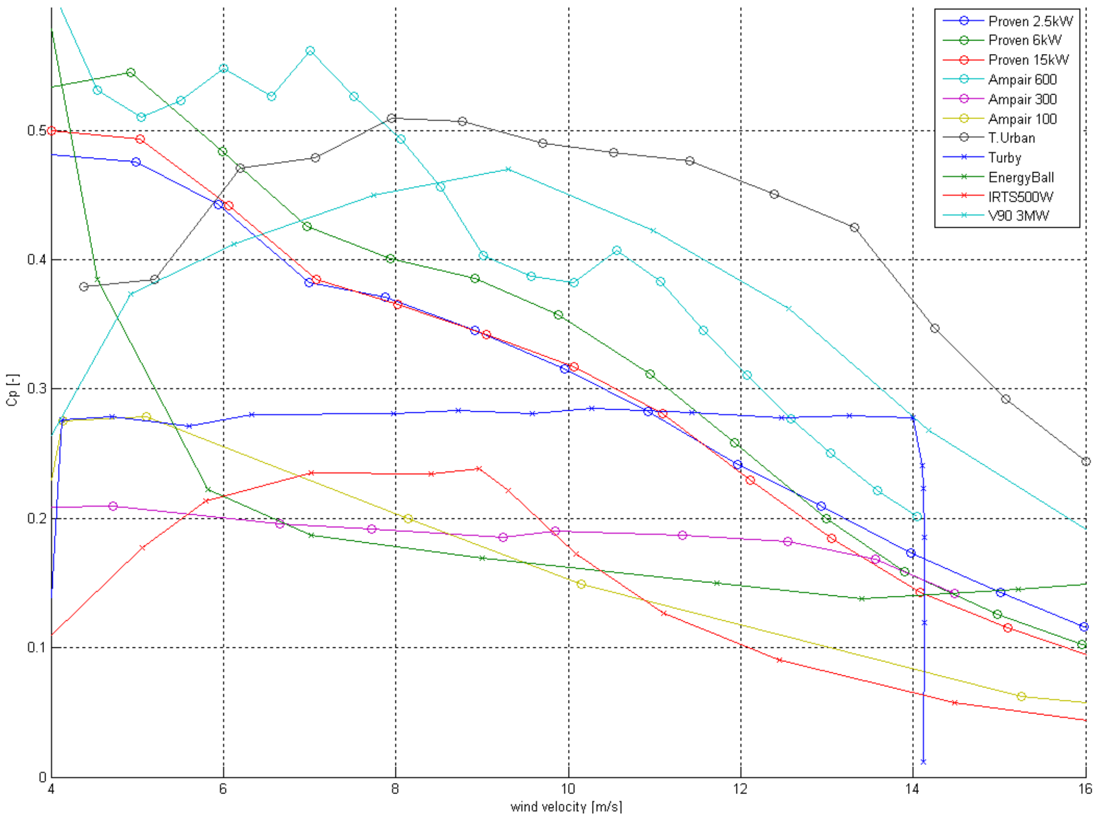


Figure 31: C_P values plotted over wind velocity, derived by reading out of charts

4.4 Small Wind Turbine Performance and Safety Standard

Within the group WINEUR a lot of research and project work was done. In February 2007 they published “Guidelines for Small Wind Turbines in the Built Environment”. There, some more pilot projects are listed. One of those is the Warwick Microwind Trial Project. Within this trial, in total 29 turbines were installed, starting in early 2007 and observations summarized in a final report in January 2009. Data and reports can be found on the corresponding homepage [xix]. In conclusion they demand a standard for the power curves, since the power curves given by the manufacturer were way off the measured power output. During the process, they worked out several standard proposals and certification schemes, which will be adopted as an international IEC standard, as soon as they are of adequate detail. Other projects suffered by vibrations, unexpected faults and damage by stormy weather (broken blades). In one case a turbine had to be stopped over night due to noise levels and also during sunny days because of flicker. The Guideline reports of 56 Urban Wind Turbines (UWT) installed in the Netherlands by December 2006, most of those on roofs of office and apartment buildings. In the UK, more than 150 turbines have been installed in urban areas by the end of 2006. Undefined standards make it difficult to install turbines in urban areas or make it easy to sell an uncertified product and with that probably the risk to harm the urban wind turbine reputation. The British Wind Energy Association came up with a national standard [lvii]. In Denmark household wind turbines up to 40m^2 follow special certification rules, which are different from the large-scale wind turbines and different from the IEC 61400-2 standard [xli]. The international standard for small wind turbines, the IEC 61400-2, is under revision.

5 WIND TURBINES IN COPENHAGEN

To circumvent the possibility of a neighbour being bothered by a turbine, although he is not gaining anything from the turbine, a solution to attain acceptance is to use turbines for public needs. They are not necessarily connected to a building, but to an advantage of all citizens. Some application ideas are described in the next chapter using the example of Copenhagen, followed by a short look at the current situation in Copenhagen.

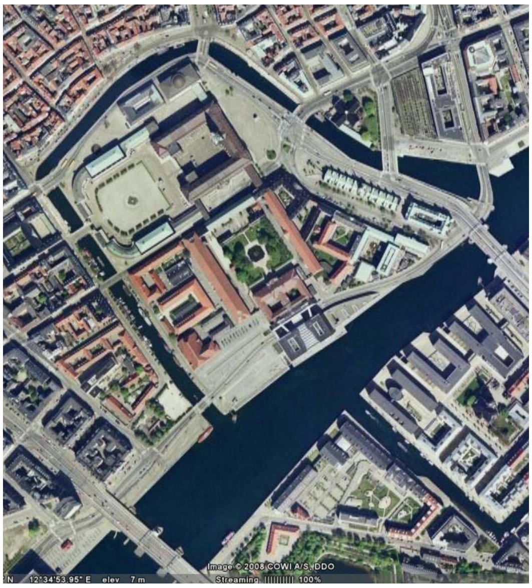


Figure 32: Detail map of Copenhagen [xlii]

5.1 Siting in Urban Areas

Copenhagen's most known characteristics are its bridges and towers. At the same time they contain the potential of carrying wind turbines. Hence, a lot of places exist to implement wind turbines in the city. Especially bridges offer interesting conditions. Why and where is discussed in the following subsections.

Water

Above channels water rules the roughness and with it influences the boundary layer shape. According to the Davenport roughness classification, the roughness length of water is stated with z_0=0.0002m [xliii] and with it comes a very blunt wind velocity profile, meaning high velocities at relatively low altitude. In comparison, the roughness length of z_0=0.5m is described as "very rough" and is common for heavy cultivated landscapes with a lot of obstacles like large farms and clumps of forest. Davenport's roughness classification defines densely built-up areas without much building height variation as "skimming" and they are handled with a roughness length of z_0=1.0m. City centres with mixture of low rise and high rise buildings are announced as "chaotic" and handled with a roughness length of z_0>2.0m, while analysis by wind tunnel is advised for roughness length categories above z_0>0.25m . The higher the roughness is the lower the velocities get (Figure 33).

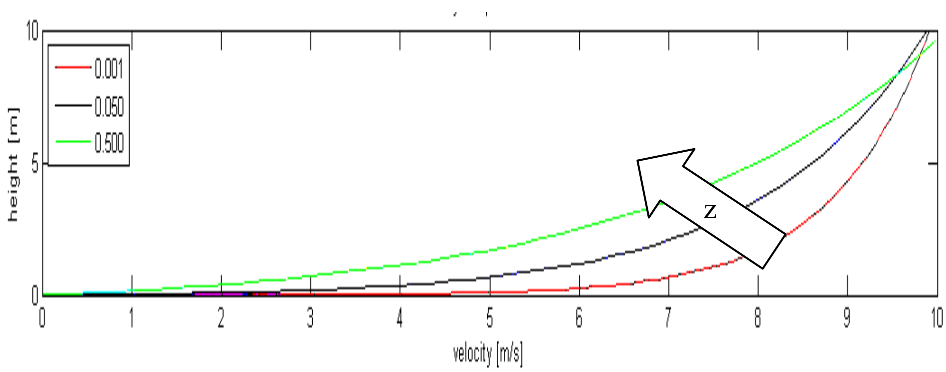
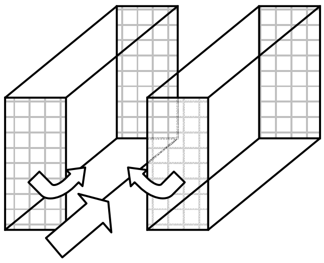


Figure 33: Boundary layer profiles as result of CFD simulations with different roughness heights (z_0=0.001 (red); 0.050 (blue), 0.500 (green)

Buildings bordering a channel are funneling the wind



The channel, taking course through the whole city of Copenhagen, is bordered by buildings. These buildings force the wind to surround them. In this way the wind is funnelled and sees the area above the channel as free field to proceed. This effect is also present in areas where buildings border big streets, mentioned earlier as the street canyon effect.

Figure 34: Buildings along the channel funnelling the wind

Energy Close to the Channel Makes Light

The energy can be used where it is produced. It can be used for lightening; save energy through the day time and transform it into light during the night time. Another idea is to use it in the adjacent buildings (see Figure 35).

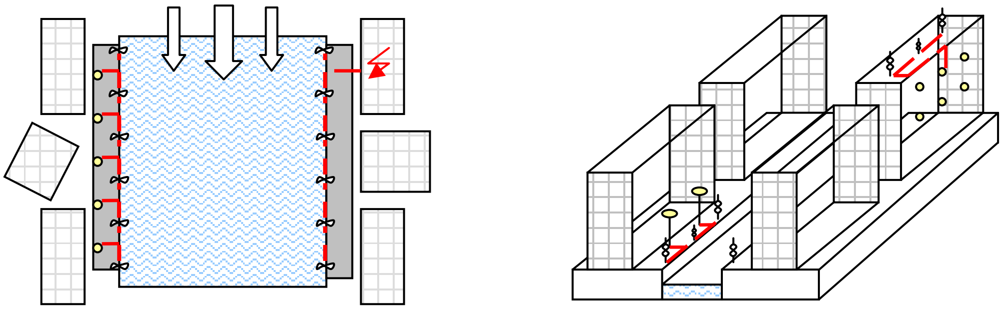


Figure 35: Power usage on-site

VAWT mounting

Most vertical axis wind turbines need a fixation on the upper end of the axis. Smaller turbines can cope without such a fixation. QuietRevolution's turbine is with a 5m height and a rated power of 6kW rather big for a small VAWT, but can still handle the moments without fixation. An idea could be to integrate turbines into the bridge tension construction (see Figure 36).

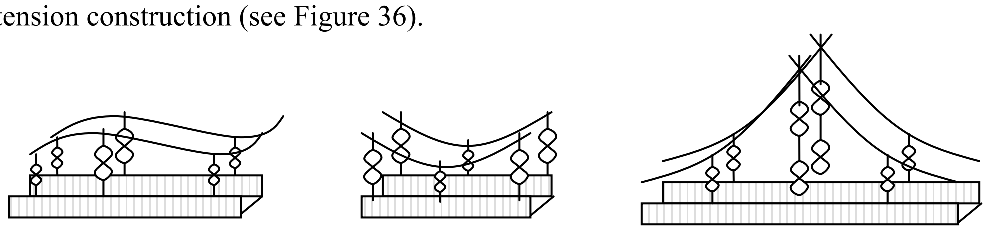


Figure 36: Vertical axis wind turbines integrated in bridge structure

Cars

In case of VAWTs installed on bridges, cars passing by induce an additional velocity to the wind velocity. On the other hand, no action occurs without reaction. The cars will experience a force as well, while the wind velocity is decelerated by the turbines. Another possibility could be to mount turbines underneath the bridge. In this way, they would be kind of hidden and at the same time risks during a failure would be reduced. Another advantage is that the wind turbines are not installed directly at the buildings and therefore the noise is not that intense. At the same time, the buildings located close to the bridge, could use the produced electricity. Should new buildings be built, the changing wind situation will affect mainly the neighbouring buildings, but not the bridge wind field.

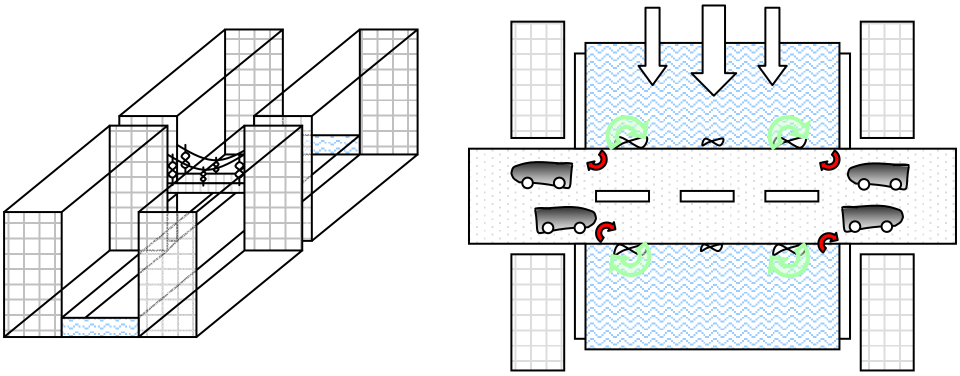


Figure 37: Bridge installation with cars passing by

Shielding

By shielding the bridge, the flow is compressed and accelerated towards the turbines. The cars are free from side wind, as long as the shielding is high enough. Care has to be taken with shielding day light. It would make additional lighting necessary and cancel out what was gained. Additional structure is a drawback. In some cases shielding is present anyway, e. g. to shield traffic noise from the inhabitants.

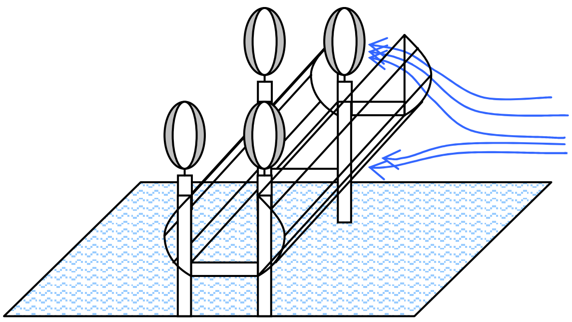


Figure 38: Bridge shielding

Different Applications

A rotationally symmetrical structure like the pavilion in Fælledparken, Copenhagen, (see Figure 39, left) offers the opportunity to install a unidirectional turbine on the top. The flow will be concentrated and accelerated towards the top and with the gained energy lights or something more symbolic, like an ice machine, could be driven. A building like the Tycho Brahe Planetarium, Copenhagen, (see Figure 39, right) is not independent from the wind direction. Its orientation towards the water is advantageous if the wind comes from the lake side, because of the low roughness of the water surface.

Figure 39: Left: Pavilion in Fælledparken [xliv]; right: Tycho Brahe planetarium [xlv]

Wind turbines in public could be coupled to an indicator, meaning that the power should not vanish in the grid. The production should be coupled directly to the usage like the Netherland wind mills milling grain and create an autonomous circuit. Autonomous circuits are operating when it is windy weather. Which application could be attractive in windy weather? High wind velocities are mostly coupled to cold and unpleasant weather. But wind turbines can be used to cheer up people with e. g. light fragile and moving structures (see Figure 40, left). At the same time they should stick to a simple design, otherwise the design could become “out of fashion” fast. In Copenhagen one on-site usage could be at the lakes. Because the water is only slowly mixing, it could have advantage of an artificial ventilation system. Turbines could be placed on the bridges separating the single basins (see Figure 40, right). Criteria to install turbines on bridges were discussed above and can be applied here as well.

Figure 40: Left: “Wind to Light”, by Jason Bruges Studio [xlvi]; right: turbine to ventilate the lakes in Copenhagen [xlvii]

Turbines in cities could be installed “off-shore” as well. Especially in parks, where people go to relax, having a picnic and play e. g. football, a turbine in the middle of the field is limiting the freedom upwards. A football, a boomerang or other flying devices are exposed to the risk of being hit by the rotating turbine blades. The same applies for the turbine, but vice versa. By erecting turbines in the middle of a small lake (without boat traffic), a natural distance is kept between the citizen and turbine. Also, a low roughness surface is surrounding the turbine, of course depending on the amount of trees in the park and their distance. As for off-shore wind turbines, more complex and expensive components have to be used in matters of waterproof housings, under water cables, etc. and installation and maintenance is more time and money intense.

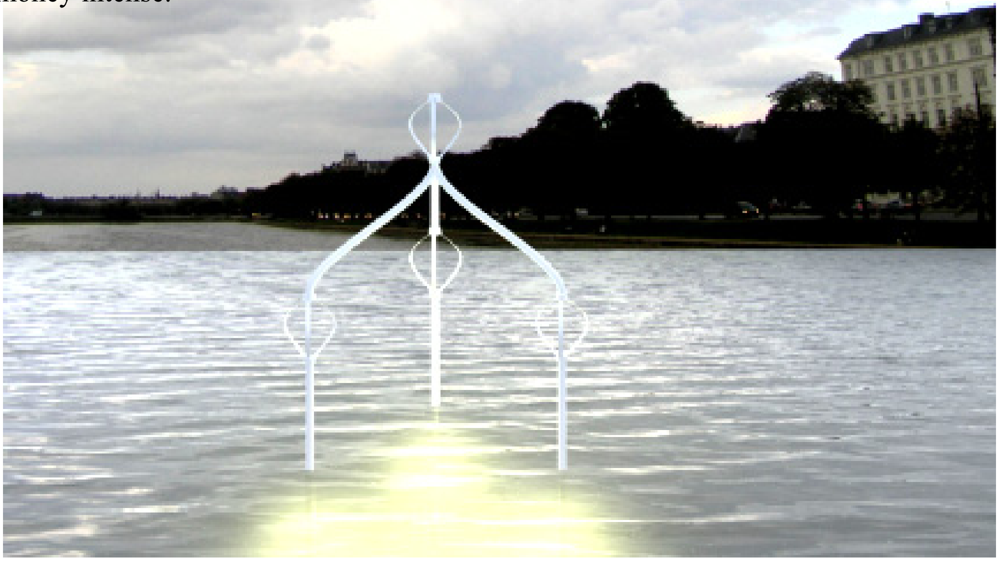
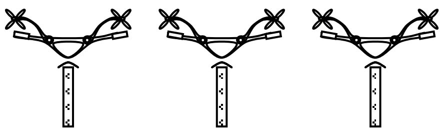


Figure 41: Off-shore turbines in city lakes, here e.g. Peblinger Sø, Copenhagen

Another solution in terms of protection could be a casing. A small HAWT in a cage, pivot-mounted and able to pitch can adjust to the changing wind directions. Especially in urban areas, mounted on rooftops e. g., the wind direction does not only change in yaw angle, but also in vertical direction. The cage surely decreases the efficiency, but ensures safety, on both sides.

Figure 42: Encased HAWT

Besides the bridges and towers, the city bikes are characteristic for Copenhagen. Turbines could be erected at the bike stations. It would couple the green thought of cycling to the green thought of wind energy. At the same time, the stations would be easy to find. The energy could be used, for example, to charge electric bikes. Energetic people could even produce energy by cycling and support charging the electric bikes.



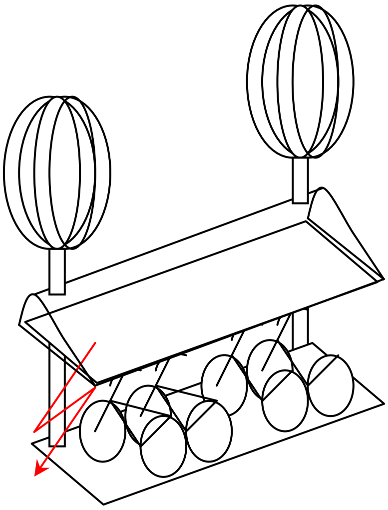


Figure 43: Wind energy and city bikes in cooperation

5.2 Status in Copenhagen 2009

December 7th to December 18th 2009 the United Nations Climate Change Conference will take place in Copenhagen. In the course of this, Copenhagen's Commune makes efforts to demonstrate the town as an eco metropolis. A big part of their investigations is in enhancing the bicycle situation, implementing more solar energy and offering more green and blue recovery environments for the citizens [[xlviii]]. In matters of wind energy, close to the shore of Copenhagen, two wind farms can be found (Middelgrund and Lynettenpark). Another initiative called Solar City Copenhagen is mainly looking into the aesthetic and at the same time efficient implementation of solar energy in buildings but they also look at other renewable energy sources [[xlix]]. CO_2 neutral buildings and sustainable districts in Copenhagen was the title of on of the conferences held by the group "Solar City Copenhagen" in April 2008. Next to solar energy, the interest exists how to design a building or a whole area energy-self-sufficient and the interest is growing. Some of the projects consider wind turbines in addition to solar panels. A short overview follows.

- CO_2 Neutral Hotel

  Henning Larsens Architects have worked out a concept for a hotel, 100% CO_2 neutral. The building shall accommodate 250 to 300 guests and their energy need shall be covered by a combination of passive solar warmth, solar warmth to heat water, solar panels, harbour water cooling, high isolating constructions, wind energy, purchase "nature electricity", LEDs, intelligent lighting and more. How and where the turbines should be placed was not visible in the conceptual designs.

- Sustainable District Plan for Valby

Jens Windeleff, representing the Energy Authority, introduced different European programs, which are working with environmentally friendly topics. Copenhagen is involved in the project “Concerto II”, which is working with the suburb Valby. It is planned to become 100% sustainable, while the Concerto project is looking mainly into solar energy. Other projects are called “Kommuneplan2009” and “MUSEC” (Multiplying Sustainable Energy Communities).

- Sustainable Plan for Carlsberg site

Signe Antvorskov, speaker for Esbensen Consulting Engineers, talked about the Carlsberg area. Old buildings shall be restored with state of the art technologies and new buildings shall be built with respect to their vision to produce in 15 to 20 years even more energy than the area will use. Some similar projects are already accomplished at Haraldsgade quater and Sundholmsvej in Copenhagen. For the Carlsberg area they consider wind turbines to support the decentralized energy system.

It seems as if wind energy in Danish cities is getting more and more interesting and would be tolerated. However, how do we find potential sites in cities for erecting wind turbines? In the following some available data bases in Copenhagen, relevant for wind turbine siting, are introduced. Actually, the first wind turbine erections in the city Copenhagen were already conducted and are mentioned after the data base chapters.

3D Data Base

Different 3D data bases of Copenhagen exist. One was once used for investigations of gas propagation, but can be used for micro wind climate predictions as well. With the information of the buildings arrangements to each other, their height and with the mean wind direction, supported by local wind measurement data, a more detailed site prediction can be made. This data base is not giving precise information about roof top shapes and at several places an update would be necessary. The Copenhagen Commune offers a free available 3D data base on their homepage [li]. On their homepage are also links to enterprises, where detailed models can be purchased. Parts of such models can be used for computational fluid dynamics simulations to detect areas of high wind energy potential or to determine the wind energy potential at a certain location.

Figure 44: Footprints of Copenhagen’s buildings, ArcExplorer

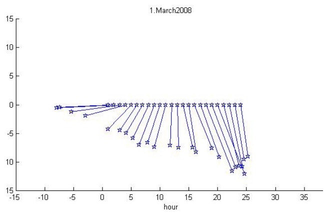
Local Wind Measurements

At several areas in Copenhagen permanent wind measurements are going on. One of the stations is e. g. located on the rooftop of H. C. Ørsteds Instituttet, a four storeys building situated at Nørre Allé, close to Fælledparken (see Figure 45).

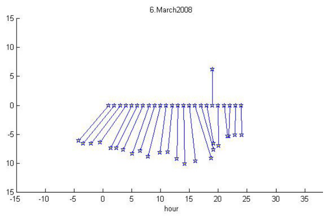
Figure 45: Situation of the H. C. Ørsteds instituttet, Copenhagen [xlii]

The mean wind direction and velocity, one hour averaged, can be found on the internet [lii]. In Figure 46 the wind vectors from 1^{st} to 15^{th} March 2008 are plotted. The very left vector indicates the wind from midnight to 1 o'clock in the morning and the very right vector indicates the wind condition between 23 o'clock and midnight. The mean wind velocity, based on this data, was in the month March 2008 4.98m/s.

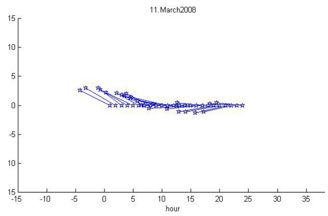
This information creates a solid base for predicting the wind turbine performance and the type of turbine to be selected. However, these plots do not show the turbulence intensity or the wind direction changes, which should also be taken into account. These data indicates the wind energy potential at that part of Copenhagen and can be used as supplementary information to other information sources.



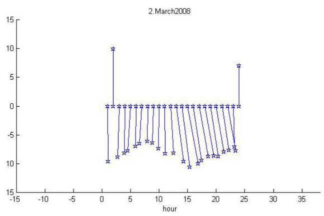
mean: 8.58m/s;



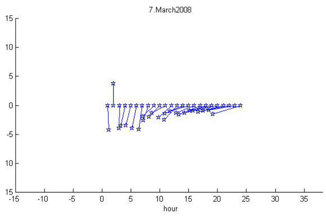
mean: 7.81m/s



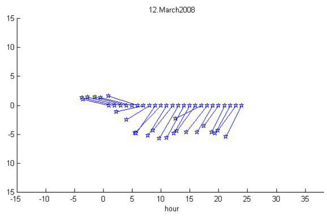
mean: 5.52m/s



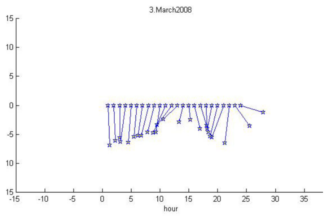
mean: 8.28m/s



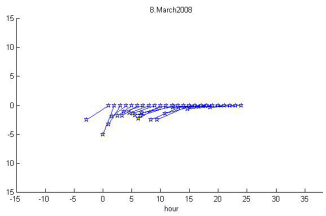
mean: 3.74m/s



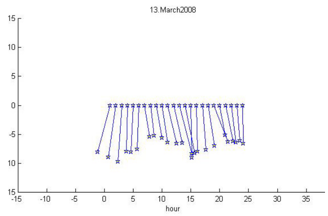
mean: 5.57m/s



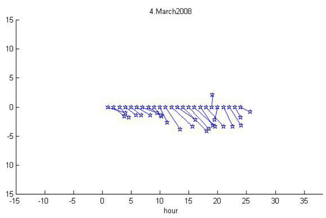
mean: 4.94m/s



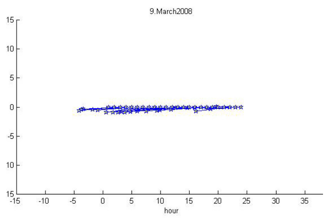
mean: 4.91m/s



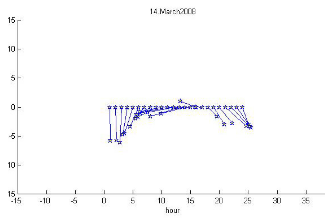
mean: 7.23m/s



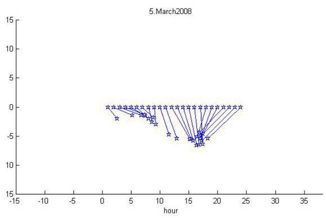
mean: 3.31m/s



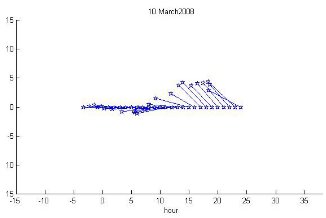
mean: 5.33m/s



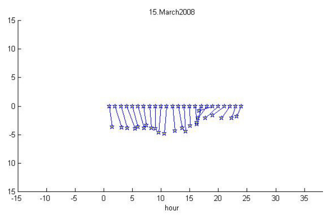
mean: 4.05m/s



mean: 5.09m/s



mean: 5.23m/s



mean: 3.52m/s

Figure 46: Wind vector plots, based on measurement data from H. C. Ørsted Instituttet

Urban Wind Turbines Installed in Copenhagen

Probably motivated by the United Nations Climate Change Conference in December 2009 in Copenhagen the first urban wind turbines have found their way into the city. The first urban wind turbine in Copenhagen was installed on the rooftop of the company Logik & Co in August 2009 (see Figure 47). The turbine weighs 178kg and the German manufacturer claims that the turbine is noiseless. Logik & Co have chosen to install a wind turbine on their own building to validate its performance and in a second step they want to offer an urban wind turbine service package, including the choice of an appropriate wind turbine and its installation, to Copenhagen's commercial but also private customers [liii].

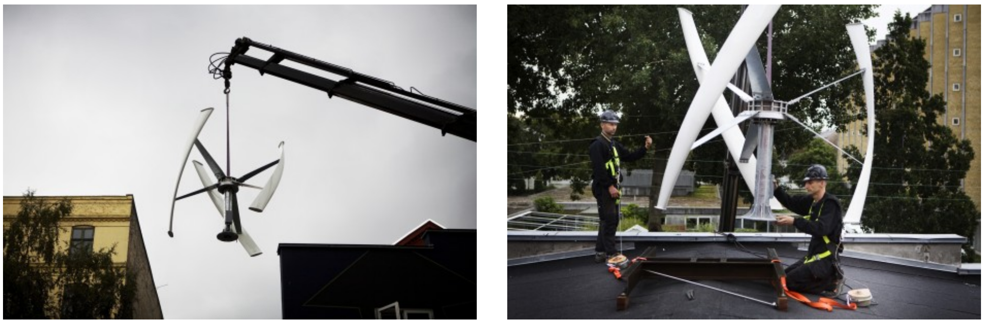


Figure 47: Installation of the first urban wind turbine in Copenhagen [liv]

A more public installation was the temporal installation of Windspire turbines [lv] at different places around the city, e. g. on a small square, in front of one of the entrances to Fælledparken, Copenhagen (see Figure 48). The wind turbines were installed by the energy group DONG energy, Denmark. As the department leader, Jan Darville said, wind turbines in cities are more of symbolic value, to bring renewable energy production into the sight of people and with that in their awareness.

Figure 48: Three demonstration VAWTs, installed on a square in the city Copenhagen [lvi]

The project was politically backed by Copenhagen's Kommune. Klaus Bondam, the current technology and environment mayor of Copenhagen's Kommune, welcomes the urban wind turbines as a label of renewable energy consciousness as long as the installations are in balance with the city environment and the city life. Financial support for the installations, however, shall not be given by the state, but the states task in this issue is to provide an unproblematic frame work for the ones, who want to install urban wind turbines on their own ground, agreed Klaus Bondam and his colleague Lars Dueholm, member of the Technology and Environment committee.

6 CONCLUSION

Three different types of urban wind turbines were categorized, 1) wind turbines integrated in buildings, 2) wind turbines mounted on existing buildings and 3) wind turbines in public spaces. Although some small scale turbines are already installed on buildings, integrated in buildings structure and also positioned besides buildings the application of urban wind energy is not explored yet. Small turbines on the current market are generally not designed for the low wind velocities and the unstable, turbulent wind conditions in urban environments. The same applies for building structures, where the constructions are not designed for the dynamic loads. Some field tests with already existing small wind turbines on buildings failed due to noise emissions, high turbulences resulted in cracked blades and vibration transmission demolished buildings. At the same time, manufacturers like Proven are entering successfully city areas with their products. More and more manufacturers make an effort to develop turbines suitable to urban areas. Knowledge about optimisation of blade design, mechanical damping, noise emission, safety procedures, generator efficiency and positioning is necessary. Besides these unsolved tasks the social acceptance and therefore the market are factors to take into account. Depending on the site a vertical or horizontal axis wind turbine is adequate. In general, small wind turbines are less efficient than large wind turbines and horizontal axis wind turbines are more efficient than vertical axis orientated ones. In scenarios, indeed, where wind directions are changing frequently and fast, horizontal axis turbines are less efficient and consequently the vertical ones become relatively more or equally efficient. A good way to enter urban areas with small-scale wind energy might be, to use the harvested energy directly and for the benefit of all citizens, while the design is simple, unobtrusive and save.

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